Quantum Fluctuations & Competing Orders in Cuprate Superconductor

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There is a general consensus that various non-universal phenomena associated with the cuprate superconductors can be attributed to competing orders in the ground state. In this context, it is conjectured that all cuprate superconductors are in close proximity to a quantum critical point (QCP) at $\alpha = \alpha_c$ that separates the pure superconducting (SC) phase from the coexisting phase of SC and a competing order, where α is a multi-dimensional material parameter related to the doping level, onsite Coulomb repulsion, attractive potential of the SC singlet, the number of CuO_2 layers per unit cell, etc. We have recently devised proper experimental signatures for elucidating these issues. As a heuristic example, we consider the spin density waves (SDW) as the competing order, and examine the evolution of SDW and SC under an external magnetic field (H) and as a function of α. Figure 1 illustrates the theoretical phase diagram by Demler et al. and that normalized for each α, and Fig. 2 depicts our experimental findings for the cuprates.

Publications emanated from this support in FY2004:

- C.-T. Chen and N.-C. Yeh, Phys. Rev. B **68**, 220505 (R) (2003).
- N.-C. Yeh *et al*, accepted for publication in the Int. J. Mod. Phys. B (2004); [cond-mat/0408100].
- N.-C. Yeh *et al*, accepted for publication in the Chinese J. Phys. (2004); [cond-mat/0408105].
- V. S. Zapf *et al*, submitted to Phys. Rev. B (2004); [cond-mat/0405072].

Fig.1: Theoretical conjecture [Demler et al. ('01); Yeh et al. ('04)]

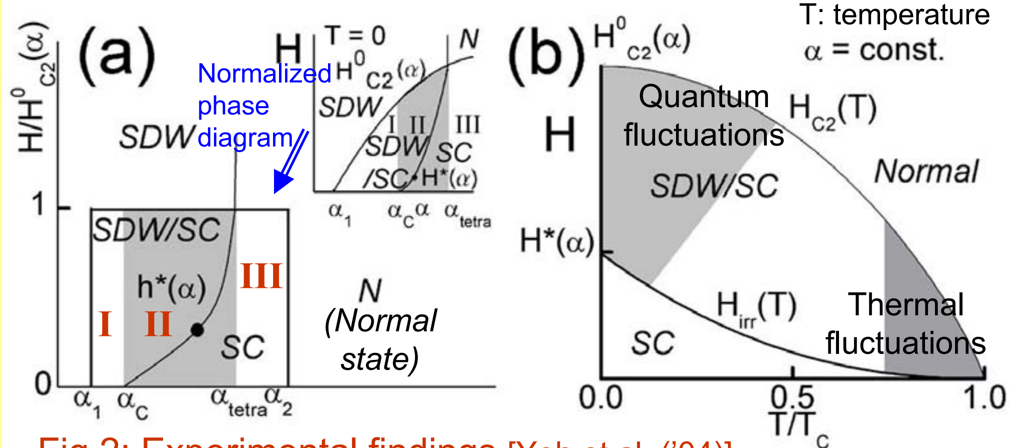
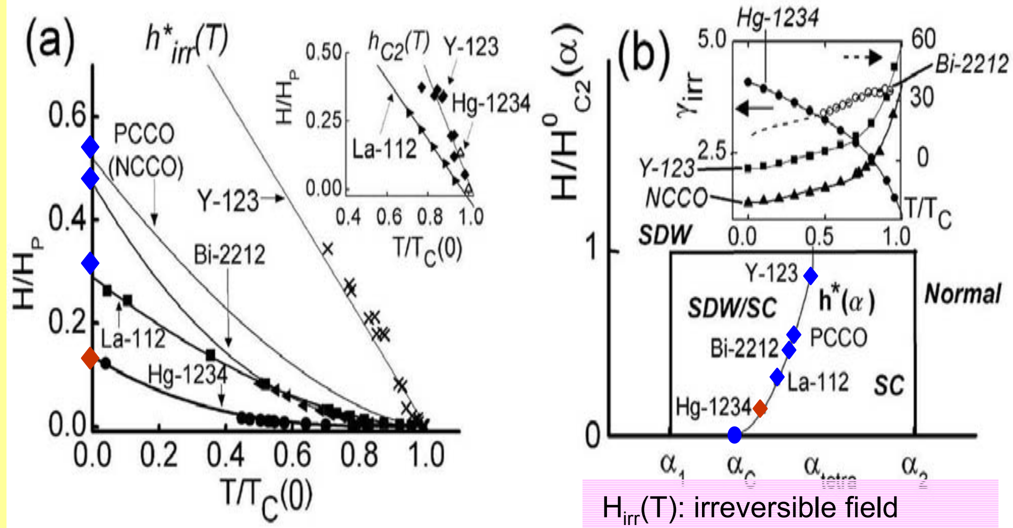


Fig.2: Experimental findings [Yeh et al. ('04)]



Hg-1234: $HgBa_2Ca_3Cu_4O_x$
La-112: $Sr_{0.9}La_{0.1}CuO_2$
Bi-2212: $Bi_2Sr_2CaCu_2O_{8+x}$
P(N)CCO: $Pr_{1.75}$ $(Nd_{1.75})Ce_{0.15}CuO_{4-x}$
Y-123: $YBa_2Cu_3O_{7-x}$

$H_{irr}(T)$: irreversible field
$H_{c2}(T)$: upper critical field
$H_{c2}^0 = H_{c2}(T=0)$
$H_p = H_{c2}^0$ (for H || ab): paramagnetic field
$h^* = H_{irr}(T=0)/H_{c2}^0$

Despite more than 18 years of intense research, the physical mechanism that leads to the occurrence of high-temperature superconductivity in the novel superconductors known as the perovskite cuprate oxides (or more simply, the cuprates) remains elusive. The primary difficulty is that there are multiple "competing orders" in the lowest energy state (known as the "ground state") of the cuprates. That is, at very low temperatures different phases separated only by very small energies can occur in the cuprates, so that superconductivity is not necessarily the dominating lowest energy state. In other words, depending on subtle tuning of either the chemical compositions of the cuprates or other controllable variables such as the temperature and applied magnetic field applied to the cuprates, high-temperature superconductivity can either homogeneously coexist with a competing phase, spatially separated from a competing phase in a "Swiss cheese" like pattern, or completely taken over by a competing phase. This phenomenon gives rise to extremely rich and complicated physical properties that appear to be "non-universal" among different families of cuprate superconductors, and is fundamentally different from conventional superconductivity where the low-temperature phase of the superconductors is decisively dominated by superconductivity.

(A metaphor that better conveys the differences between high-temperature and conventional superconductivity to non-specialists is to compare the map of Europe versus that of China: the former consists of multi-nations of comparable sizes and political/economical power, whereas the latter comprises of one large nation with relatively homogeneous culture.)

Our research has focused on unraveling the ground-state properties of the competing orders in the cuprate superconductors because we believe that the key to unravel the mystery of high-temperature superconductivity lies in developing thorough understanding for the nature of the competing orders and their interplay with superconductivity. Our experimental approaches involve both "thermodynamic" measurements that determine the macroscopic nature of different phase transformations and "microscopic" measurements utilizing a scanning tunneling microscope (STM) that provides physical information of different phases down to nanometer and atomic scales.

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The proximity of each cuprate superconductor to a QCP at α_c can be characterized by the reduced zero-temperature irreversibility field h*, with smaller h* indicating closer proximity to the QCP. A small h* implies that excess low-energy excitations due to the coexistence of competing order with SC can be induced either by magnetic field (H) or temperature (T), as illustrated in Fig. 3 (after H.Y. Chen and C.S. Ting). The correlation between the microscopic quasiparticle spectra and the thermodynamic quantity h* can be exemplified in Fig. 4: (a) the superconducting energy gap Δ determined from the tunneling spectra decreases more rapidly with T for smaller h* (also see Fig.2); (b) the tunneling spectra of La-112, which has a smaller h*, cannot be fully accounted for by quasiparticle excitations of a pure SC, whereas the low-energy ($|E| < \Delta$) excitations of Y-123 with a much larger h* can be reasonably fitted with quasiparticle spectra of $d_{x^2-y^2}$-wave SC.

Trainees involved in this research:

- Graduate students: Ching-Tzu Chen, Andrew D. Beyer, Cameron R. Hughes;
- Postdoctoral scholar: Vivian S. Zapf;
- Undergraduate student: Timothy Ward.

Honor received by the PI:

- Outstanding Alumni Lectureship, Department of Physics, National Taiwan University (2003).

Fig.3: Theor. H & T evolution of SDW/SC [Chen & Ting (2004)]

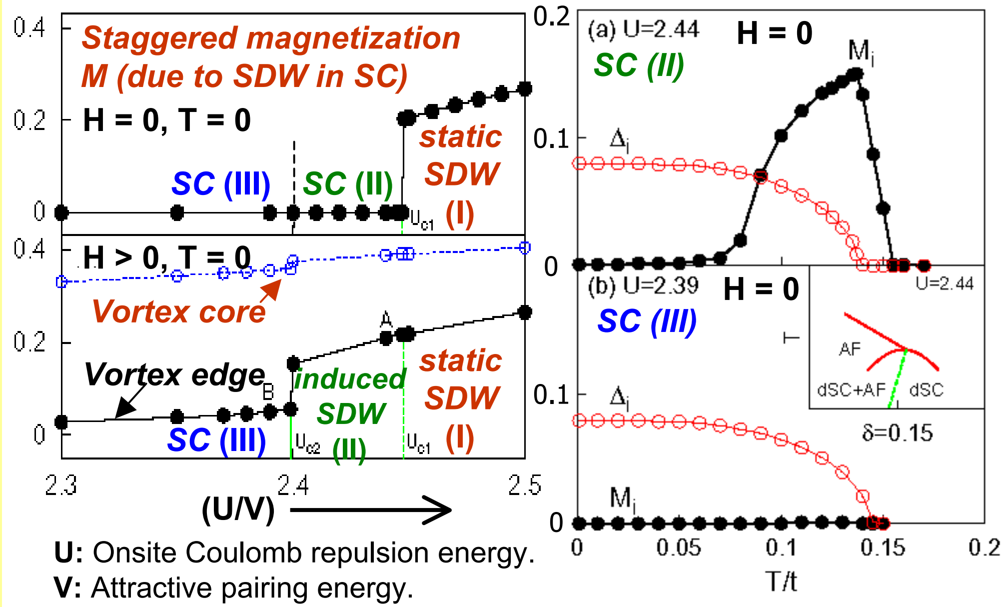
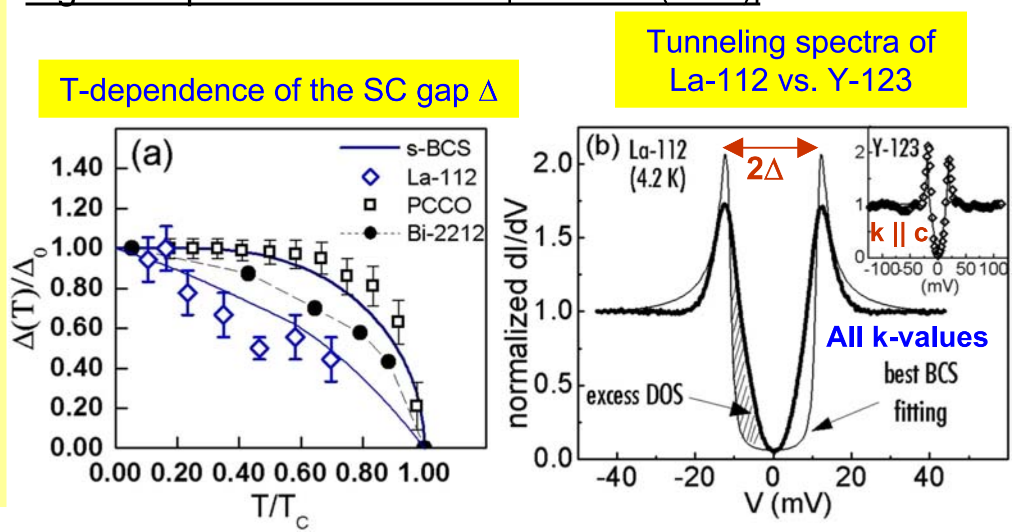


Fig.4: Empirical confirmation [Yeh et al. (2004)]



Besides unraveling the fundamental mechanism for high-temperature superconductivity, understanding the issues of competing orders in cuprate superconductors can help control properties of these materials crucial for device applications as a function of the chemical compositions, temperature and magnetic field.

Our verification of competing orders in the cuprate superconductors involves the use of both macroscopic and microscopic experimental probes. The microscopic probe used to obtain the data here is a variable-temperature scanning tunneling microscope (STM) that provides imaging and spectroscopic properties of the superconductor down to the atomic scale. The specific spectroscopic properties obtained by an STM are the differential conductance (dI/dV), which are determined by measuring the tunneling current (I) from the sharp STM tip to the sample through a small vacuum gap while the tip and the sample surface are biased at a relative voltage (V). The differential conductance can provide important information about the physical characteristics of the superconducting sample, including the superconducting "energy gap" that is a measure of the "strength of superconductivity", and the properties of the "low-energy excitations" (known as the "quasiparticles") that are associated with the physical state of a superconductor slightly above its ground state.

The differential conductance can vary spatially if there are phase separated competing orders, or can exhibit excess low-energy excitations beyond those for a pure superconductor if superconductivity coexists with a competing order homogeneously throughout the sample. Moreover, the decrease in the superconducting energy gap (or the superconducting strength) with increasing temperature (T) or magnetic field (H) will be more rapid if competing orders exist in a superconductor. Our experimental data depicted here provide evidence for the existence of competing orders in all cuprate superconductors under investigation. In addition, we find that competing orders in most cuprate superconductors tend to coexist homogeneously with superconductivity, which is an important finding.

Besides the scientific findings, it is worth mentioning that the variable-temperature STM used in this work is a home-made piece of apparatus, and students involved in this work have all contributed to various aspects of the instrumentation development besides performing measurements.